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CRITICALITY STUDIES

CRITICALITY DATA AND NUCLEAR SAFETY GUIDE APPLICABLE TO THE OAK RIDGE GASEOUS DIFFUSION PLANT

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Oak Ridge Gaseous Diffusion Plant
Oak Ridge, Tennessee

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CRITICALITY DATA

AND

NUCLEAR SAFETY GUIDE

APPLICABLE TO

THE OAK RIDGE GASEOUS DIFFUSION PLANT

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ABSTRACT

The available minimum experimental and theoretical criticality information for U-235 enrichments of 1% - ~ 90% are presented together with the fundamental nuclear safety control criteria currently in effect at ORGDP. The fundamental nuclear safety criteria remain essentially unchanged from the previous edition of the report with the exception of the extension of nuclearly safe variables under 5% U-235 enrichment, the increase of the minimum U-235 enrichment considered to be non-reactive from 0.71% to 0.90%, and a statement of a new mass-volume principle. Other additions include guides for computing a solid angle and applying nuclearly safe variables to uranium materials, other than metal, of intermediate densities.

CRITICALITY DATA AND NUCLEAR SAFETY GUIDE APPLICABLE TO THE OAK RIDGE GASEOUS DIFFUSION PLANT

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USE OF K-1019

Although this report has been prepared specifically for gaseous diffusion plant operations, it is realized, of course, that there are probably many other types of operations for which the guide may be generally useful, and it is understood that the document has proven useful in many other installations. It therefore becomes important to re-emphasize for such users, as well as ORGDP personnel, that the criteria presented herein are considered specifically applicable only for the U-235 materials normally encountered in the Oak Ridge Gaseous Diffusion Plant, and for operation under the limitations given in the section on Basic Assumptions; the most important of these are probably density and the types of moderators and reflectors available. Thus, while the conclusions drawn are considered applicable for diffusion plant operations and useful elsewhere, it is perhaps obvious that they may not necessarily be appropriate for other production or laboratory facilities. In particular, extreme caution should be exercised in the use of these data, if at all, for high density uranium materials, particularly metal, and not at all for other fissionable materials such as U-233 or plutonium; information on all of these materials is now generally available and may be obtained in reports such as K-1380,* TID-7016,** and TID-7019.***

* Henry, H. F., et al., Studies in Nuclear Safety, 8-14-58 (K-1380)

** Callihan, A. D., Ozeroff, W. J., Paxton, H. C., and Schuske, C. L., Nuclear Safety Guide, published in 1958 (TID-7016)

*** Henry, H. F., et al., Guide to Shipment of U-235 Enriched Uranium Materials, to be issued (TID-7019)

CHAPTER 1

INTRODUCTION TO FIFTH REVISION

As in previous editions, the current revision of this report, which has been retitled, summarizes the available minimum experimental and theoretical criticality data for homogeneous uranium systems at U-235 enrichments of 1% - ~ 90% and incorporates the conclusions drawn from these data as applicable to specific plant conditions. Major changes in the nuclear safety criteria, which are based on recent experimental and theoretical work, include the extension of the nuclearly safe variables for U-235 enrichments below 5%, the increase of the minimum U-235 enrichment considered to be non-reactive from 0.71% to 0.90%, and the statement of a new mass-volume principle. Other additions, which the authors hope will enhance the value of the guide, include methods for computing a solid angle and a conservative method for applying nuclearly safe variables to uranium materials, other than metal, of intermediate densities. It may be noted that the tabular values in the tables are given in both metric and English units.

In addition to its own theoretical work on problems of general and specific plant interest, the ORGDP has continued to collaborate in planning the basic criticality research program which provides experimental data for the continuing evaluation of the nuclear safety of plant design and operations. As in previous editions, all criticality design and operational criteria have been approved by the ORGDP Criticality Hazards Committee and the ORGDP Criticality Hazards Consultants' Committee. A chart showing the organization for nuclear safety at the ORGDP, as outlined by plant management, is also included.

The assistance of Mr. W. A. Johnson and Dr. J. R. Knight of the ORGDP Nuclear Safety staff in the preparation of material for this fifth revision is gratefully acknowledged as is the courtesy of Dr. A. D. Callihan and his staff of the ORNL Criticality Laboratory in providing unpublished experimental data.

INTRODUCTION TO ORIGINAL EDITION*

In view of the importance of criticality considerations in the design and operation of the K-25 units, a summary of available criticality information and plant design and operation criteria has been prepared. Experimental data, which are given, have been used as the bases for determining the best estimated values for the basic critical mass information.

The basic design and operational criteria given have been approved by the K-25 Special Hazards Consultants' Committee and its forerunners of the early days of plant operation. The methods of meeting these design and operational requirements have been largely developed by the K-25 special hazards field groups working with the Approvals Committee and reporting to the K-25 Special Hazards Committee.

The authors would like to acknowledge the constructive reviews of this compilation by Dr. R. L. Macklin of the K-25 laboratories, Mr. J. W. Morfitt of the Y-12 criticality hazards organization, and Dr. A. D. Callihan, director of criticality research at X-10.

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* Issued on October 5, 1951, as KS-240, Basic Critical Mass Information and Its Application to K-25 Design and Operations. Subsequent revisions issued as K-1019 on 6-8-53, 12-6-54, 12-30-55, 8-2-57, and 5-23-58 (deleted)

CHAPTER 2

BASIC INFORMATION

2.1 EXPERIMENTAL DATA

The data listed in tables I through IV were taken from experiments with homogeneous uranium materials other than metal and were used in estimating the minimum mass and geometry variables from which the various safe operating criteria were derived. While several generalizations have been drawn from the more plentiful high enrichment data, it is recognized that it would be extremely fortuitous if the values given represent the true values which would be possible with unlimited data. Hence, the generalizations which are listed for each table should be considered as guides only.

1. Lowest Critical Masses

TABLE I
LOWEST EXPERIMENTAL CRITICAL MASSES

Core Material	Enrichment (wt. % U-235)	Geom.	Container	Moderation (H/U-235)	Reflector	Dimensions (cm.)	Dimensions (in.)	Solution Height (cm.)	Solution Height (in.)	U-235 Mass (kg.)	U-235 Mass (lb.)	Ref.
UO_2F_2	~ 90	Sphere	Aluminum	524	Water	32.0	12.6μ	-	-	0.84	1.85	1
UO_2F_2	~ 90	Cyl.	Aluminum	499	Air	38.1	15μ	27.4	10.8	1.63	3.59	2
UO_2F_2	~ 90	Cyl.	S. Steel	499	Water	30.5	12μ	26.3	10.4	1.00	2.21	2
UO_2F_2	~ 90	Cyl.	S. Steel$^{\alpha}$	499	Water	30.5	12μ	32.8	12.9	1.25	2.76	2
UO_2F_2	~ 90	Cyl.	S. Steel	499	Air	38.1	15μ	27.0	10.6	1.61	3.55	2
UF_6C	~ 90	Cube	None	None	Paraffin	25.4	10λ	-	-	48.8$^{\sigma}$	108	3
UF_6C	~ 90	Cube	None	None	Air	25.4	10λ	-	-	48.8$^{\sigma}$	108	3
UO_2F_2	44.6	Cyl.	S. Steel	493	Water$^{\pi}$	30.5	12μ	33.7	13.3	1.26	2.78	4
UF_6C	37.5	Cube	Rubber Sheet	None	Water and Paraffin	53.3	21λ	-	-	183.8	405	5
UF_6C	37.5	Cube	Rubber Sheet	10.7γ	Water and Paraffin	33.0	13λ	-	-	28.4	62.6	5
UF_6C	37.5	Pseudo Cyl.	None	None	Air	84.5	33.3μ	-	-	467	1030	6
UF_6C	29.8	Cube	None	128	Paraffin	27.9	11λ	-	-	4.0$^{\nu}$	8.82	7
UF_6C	18.8	Cube	Rubber Sheet	None	Water and Paraffin	91.4	36λ	-	-	452	997	8
UO_2SO_4	14.7	Sphere	S. Steel	650	Water	30.5	12μ	-	-	0.717β	1.58	9
UF_6C	12.5	Cube	Rubber Sheet	3.4	Water and Paraffin	91.4	36λ	-	-	300δ	662	8
UO_2F_2	4.9	Cyl.	Aluminum	530	Water	38.1	15μ	44.7	17.6	2.2	4.85	10
UO_2F_2	4.9	Cyl.	S. Steel	645	Air	50.8	20μ	45.7	18.0	3.3	7.28	10
UF_6	2.0	Cyl.$^{\psi}$	S. Steel	4	Water	76.2	30μ	-	-	123$^{\sigma}$	271	11
UF_4-$C_{25}H_{52}$	2.0	Pseudo Cyl.	None	400γ	Paraffin and Plexiglas	58.4	23μ	-	-	6.5	14.3	8
UF_4-$C_{25}H_{52}$	2.0	Pseudo Cyl.	None	294γ	Air	71.1	28μ	-	-	14.1	31.1	12
UO_3	1.02*	-	-	~ 500	-	∞	∞	-	-	∞	∞	13

α 0.02 in. cadmium shield (~ 0.44 g./cm.^{2}).
μ Diameter.
λ Edge Length.
ν Value considered high due to inhomogeneities.
β Multiplication of approximately 3 observed.
σ Multiplication of approximately 2 observed.
γ Optimum moderation probably higher.
π No reflector on top and bottom.
δ Multiplication of approximately 100 observed.
ψ The UF_6 was in four 30" x 6' cylinders in contact.
* Indirect method of measuring k_{∞}.

Generalizations from table I

(1) The smallest measured critical mass of U-235 is 0.84 kg.
(2) Removal of the reflector increases the minimum critical mass by 83%.
(3) The use of thin stainless steel containers instead of aluminum containers increases the minimum reflected critical mass by 12%, but decreases the minimum unreflected critical mass slightly.
(4) A cadmium shield of 0.02 in. thickness (~ 0.44 g./cm^2) increases the minimum reflected critical mass for thin stainless steel containers by 25%.
(5) From experiments not quoted in table I:

   (a) Stainless steel is as good a reflector as water for thicknesses up to 2.5 in., and there are indications that for greater thicknesses it is better than water.[14]
   (b) Reflection by a 6 in. thick concrete slab immersed in water is equivalent to that of water alone.[15]

2. Minimum Critical Geometries

The data which are presented in tables II, III, and IV give information for UO_2F_2 water solutions, except for the 2% U-235 enriched experiments which were conducted with UF_4-$C_{25}H_{52}$ mixtures.

TABLE II
EXPERIMENTAL MINIMUM CRITICAL CYLINDER DIAMETERS

Enrichment (wt. % U-235)	Container	Moderation$^{\eta}$ (H/U-235)	Reflector	Minimum Critical Diam. (cm.)	Minimum Critical Diam. (in.)	Maximum Non-Critical Diam. (cm.)	Maximum Non-Critical Diam. (in.)	Ref.
~ 90	Aluminum	52.9	Water	15.2	6.0	14.0	5.5	2
~ 90	Aluminum	44.3	Air	22.3	8.76	20.3	8.0	15,2
~ 90	S. Steel	44.3	Water	15.2	6.0	-	-	15
~ 90	S. Steel$^{\alpha}$	62.7	Water	20.3	8.0	17.8	7.0	2
~ 90	S. Steel	74.6	Air	22.9	9.0	20.3	8.5$^{\beta}$	15
4.9	Aluminum	530$^{\xi}$	Water	38.1	15.0	-	-	10
4.9	S. Steel	530$^{\xi}$	Water	38.1	15.0	30.5	12.0	10
2.0	None	294$^{\gamma}$	Paraffin and Plexiglas	50.8	20.0	-	-	12
2.0	None	294$^{\gamma}$	Air	61.0	24.0	-	-	12

η Moderation for shortest critical length measured; probably near optimum moderation except as noted.
ξ Optimum moderation probably much lower.
γ Optimum moderation probably at H/U-235 ratio of 450.
α 0.02 in. cadmium shield (~ 0.44 g./$cm.^2$).
β Solution height 80 in., H/U-235 ratio 66.0.

TABLE III
EXPERIMENTAL MINIMUM CRITICAL SLAB THICKNESSES

Enrichment (wt. % U-235)	Container	Moderation[η] (H/U-235)	Reflector	Slab Dimensions (cm.)	Slab Dimensions (in.)	Slab Thicknesses (cm.)	Slab Thicknesses (in.)	Ref.
~ 90	Lucite	44.7	Water and Lucite	113x147	45x58λ	5.1	2.0[ι]	16
~ 90	Aluminum	26.9	Water	76.2	30.0μ	5.7	2.3	1
~ 90	Aluminum	57.0	Water (½)	76x152	30x60λ	8.4	3.3	15
~ 90	Aluminum	44.3	Air	76.2	30.0μ	13.7	5.4	15
~ 90	S. Steel	62.6	Water	30.5	12.0μ	12.3	4.8	2
~ 90	S. Steel[α]	56.7	Water	30.5	12.0μ	15.8	6.2	2
4.9	Aluminum	530ξ	Water	50.8	20.0μ	25.4	10.0	10
4.9	Aluminum	645ξ	Air	76.2	30.0μ	28.9	11.4	10

η Moderation for shortest critical height measured; probably near optimum moderation except as noted.
λ Edge lengths of parallelepiped.
ι This value is probably low since part of the reflector was lucite.
μ Diameter of cylinder.
α 0.02 in. cadmium shield (~ 0.44 g./cm.^{2}).
ξ Optimum moderation probably lower.

TABLE IV
EXPERIMENTAL MINIMUM CRITICAL VOLUMES

Enrichment (wt. % U-235)	Container	Moderation[η] (H/U-235)	Reflector	Diameter (cm.)	Diameter (in.)	Height (cm.)	Height (in.)	Volume (liters)	Volume (in.^{3})	Ref.
~ 90	Aluminum	43.2	Water	20.3	8.0μ	18.6	7.3	6.05	369	17
~ 90	Aluminum	47.3	Water	23.0	9.07ρ	-	-	6.32[κ]	386	15
~ 90	Aluminum	50.1	Air	30.5	12.0μ	22.6	8.9	16.5	1007	17
~ 90	S. Steel	58.8	Water	20.3	8.0μ	20.8	8.2	6.74	411	2
~ 90	S. Steel[α]	31.6	Water	25.4	10.0μ	21.1	8.3	10.69	652	2
~ 90	S. Steel	62.7	Air	25.4	10.0μ	21.7	12.5	16.05	979	2
4.9	Aluminum	530ξ	Water	38.1	15.0μ	44.7	17.6	51.0	3110	10
4.9	S. Steel	530ξ	Air	50.8	20.0μ	38.6	15.2	78.2	4770	10

η Moderation for minimum critical volumes measured; probably near optimum moderation except as noted.
μ Diameter of cylinder.
ρ Diameter of sphere.
κ The critical volume lacked 80 cc. of filling the spherical reactor.
α 0.02 in. cadmium shield (~ 0.44 g./cm.^{2}).
ξ Optimum moderation probably lower.

Generalizations from tables II, III, and IV

(1) The minimum critical reflected cylinder diameter is probably greater than 5.5 in. but less than 6 in. In addition, the minimum critical values of the slab thickness and the volume for a reflected geometry are no greater than 2.3 in. and 6.05 liters, respectively.
(2) Removal of the reflector increases the minimum critical cylinder diameter in the order of 50% and more than doubles the minimum critical slab thickness and volume.
(3) The use of 1/16 in. thick stainless steel as a container increases slightly the minimum critical slab thickness and volume. From data not quoted in table II, it may be implied that steel has a similar effect on the minimum critical cylinder diameter;[2] however, for steel reflectors larger than 2.5 in., it may be further implied that these variables would be decreased slightly.
(4) A cadmium shield of 0.02 in. thickness ($\sim$ 0.44 g./cm.^{2}) increases the minimum critical cylinder diameter by about 25%, the minimum critical slab thickness by about 25%, and the minimum critical volume by about 60%.
(5) Paraffin is essentially equivalent to water as a neutron reflector; however, materials such as Plexiglas and Lucite appear to be slightly more effective than water as reflectors.

3. Interaction Experiments

a. The following results are limiting values as determined from interaction experiments:

(1) With aluminum reactors of identical geometry and fuel at $\sim$ 90% U-235 enrichment:[18,19]

(a) The smallest measured critical mass for 2 interacting and reflected reactors was 680 g. of U-235 per reactor.
(b) Two 5 in. diameter reactors with water reflector can be made critical when in contact and when separated by as much as 1.65 in. of water; under similar conditions, 7 such reactors can be made critical up to a separation of 4.0 in.
(c) Seven 6 in. diameter reactors in hexagonal array still interact when separated by 12 in. of water; however, the mass per reactor was about 98% of the critical mass of a similar isolated reactor.
(d) The interaction effect in air at a separation of 66 in. between 2 unreflected 6 in. thick slab reactors, which were subcritical when isolated, was sufficient to attain criticality; however, the mass per reactor was about 75% of the corresponding critical mass for a similar isolated container.

(2) With identical cubic reactors assembled from aluminum boxes which contained gylcerol tristearate-U_3O_8 mixtures at 5% U-235 enrichment:[20]

(a) Interaction effects were noted when the reactors were immersed in water and spaced 12 in. apart; however, the critical mass per reactor was 97% of the mass for a similar critical reactor completely reflected.
(b) When the reactors were separated by a distance of 12 in., the critical mass of the system was the same whether both reactors were individually completely reflected or the system was reflected but no reflector was between the reactors.
(c) When the individual reactors were completely reflected, the critical mass of the system was greater at separation distances between 2 in. and 12 in. than at similar distances with the system reflected and with air as the separating medium, but was slightly smaller for separations less than 2 in. and more than 12 in.
(d) With a void between the reactors but with the system otherwise completely reflected, the critical mass per reactor for a separation of 16 in. was 102% of the mass for a similar individual critical reactor completely reflected, and 92% of the mass for a similar individual critical reactor which was reflected on 5 sides only.

(3) With 2 aluminum reactors of non-identical geometries but identical H/U-235 ratios at ~ 90% U-235 enrichment, the spacing required for criticality for an interacting 10 in. diameter cylinder and a 47.5 in. wide x 6 in. thick slab, each containing uranium solution at an H/U-235 ratio of 330, was less than the average of the spacings at criticality when each reactor interacts with an identical "twin".[21]
(4) With 2 identical 10 in. alumium reactors containing uranium solutions at ~ 90% U-235 enrichment but different H/U-235 ratios, the solution height of the system approached that value for the individual cylinder with the lowest critical height as the separation between these reactors was increased.[21]
(5) Two 10 in. diameter aluminum reactors at ~ 90% U-235 enrichment having different H/U-235 ratios and different solution heights were subcritical at the same separation at which each was critical when interacting with its "twin".[21]
(6) An interaction effect was observed between uranium blocks consisting of a non-hydrogenous mixture of UF_4 and CF_2 at 37.5% U-235 enrichment and a slab geometry of UO_2F_2 solution at ~ 90% U-235 enrichment. When each interacting component was half the thickness of a similar unit which was individually critical, it was noted that the systems of 2 "half-slabs" were subcritical at all separations for which each slab was critical with a "twin".[21]

b. The following conclusions were drawn from interaction experiments:

(1) With uranium at ~ 90% U-235 enrichment:[19,22]

(a) For identical calculated multiplication factors, interaction is more effective between slab geometries than between non-slab geometries.
(b) The interaction effect is no greater for a system which has its components half reflected than for an unreflected system; however, a half-reflected system in itself is more reactive than an unreflected system.
(c) With a multiunit system, it is possible to have more reactivity unreflected than if the system is immersed in a moderating and reflecting medium.
(d) The effect of interaction between reflected containers drops off rapidly for separations beyond a few inches, and the interaction appears to be quite small for separations greater than 8 in.; thus, containers which are separated by 12 in. of water are essentially isolated from each other.

(2) With uranium at 5% U-235 enrichment, a system of 2 reactors is at least as reactive if the system were completely water reflected but with no reflector between the reactors as it is if each unit were completely water reflected, provided the units are separated by at least 1 ft.[20]
(3) With non-identical reactors:[21]

(a) The separation for criticality between 2 interacting dissimilar containers is less than the average of the corresponding separations at which each container would be critical when interacting with its "twin", with the exception of a well-moderated unit and a dry unit at separations of the order of a few inches.
(b) Interaction among non-symmetrical components of a system is less effective than that where the components are symmetrical.

4. Neutron Poisons and Special Geometries

A few criticality experiments were made with neutron poisons and special geometrical configurations to show their effect on the overall criticality conditions of ~ 90% U-235 enrichment UO_2F_2 solutions. The results, which are presented in tables V and VI, should be considered as tentative only, since the true experimental minima for these special variables have not been established conclusively.

TABLE V

EFFECT OF NEUTRON POISONS ON CRITICALITY OF UO_2F_2 SOLUTIONS

Container[π]	Moderation (H/U-235)	Poison	Container Dimensions (cm.)	Container Dimensions (in.)	Critical Ht. (cm.)	Critical Ht. (in.)	Maximum Non-Critical Ht. (cm.)	Maximum Non-Critical Ht. (in.)	Ref.
S. Steel Cylinder (1/4 in. Cu. clad)	50	Copper Bar	25.4 (diameter of copper bar, 4 in.)	10.0	30.2	11.9	ζ	ζ	8
Aluminum Cylinder	73ξ	Cadmium Liner[α]	25.4	10.0	64.1 (H_2O annulus, 6 in. I.D.)	25.2	122.0 (Cd. H_2O annulus 6 in. I.D.)	47.8	1
Aluminum Cylinder	73ξ	Cadmium Liner[α]	25.4	10.0	76.8 (air annulus, 6 in. I.D.)	30.2	122.0 (Cd. air annulus, 6 in. I.D.)	47.8	1
S. Steel Cylinder	73	Steel Rods[υ]	38.1	15.0	95.4 (136 rods)[+]	37.6	107.8 (139 rods)[++]	42.4	23
Aluminum Slab	79	Boral Partition[τ]	76x152	30x60	17.6 (10 partitions, 5.9 cm. apart)	6.9	(12 partitions, 4.9 cm. apart)		24
Two Aluminum Slabs	330	2 Boral Liners[τ]	7.6x121	3x47.5	38.1 (2.75 in. separation, H_2O)	15.0	117 (2.75 in. separation, H_2O, Boral)	46	8

π All containers water reflected except top; the 30x60 in. slab was only 1/2 water reflected.
ζ Estimated to be subcritical with a central copper bar with ~ 30% of the core volume.
ξ Optimum moderation probably lower.
α 0.02 in. thick (~ 0.44 g. Cd./cm.^{2}).
υ 7/8 in. diameter.
τ 3/8 in. Boral sheet (~ 0.3 g. B/cm.^{2}).
\+ Rods occupied 49.2% of core volume.
++ Rods occupied 50.5% of core volume.

TABLE VI

EFFECT OF SPECIAL GEOMETRY ON CRITICALITY OF UO_2F_2 SOLUTIONS

Container	Moderation (H/U-235)	Reflector	Geometry	Critical Diam. (cm.)	Critical Diam. (in.)	Maximum Non-Critical Diam. (cm.)	Maximum Non-Critical Diam. (in.)	Ref.
Aluminum	44.3	Water	90° cross	12.7	5.0*	10.2	4.0	15
Aluminum	44.3	Air	90° cross	-	-	19.1	7.5	15
Aluminum	73.4	Water	30° lateral	12.7	5.0**	-	-	15

* Critical height in vertical arm was 14.6 cm. above the intersection of the center lines.
** Critical height in vertical arm was 39.6 cm. above the intersection of the center lines.

2.2 BEST VALUES IMPLIED FROM EXPERIMENTS

In the following tables, the mass and volume variables were obtained from experimental data that have been corrected to spherical geometry by elementary pile theory methods[25] using extrapolation distances of 2.5 cm., which is approximately correct for unreflected assemblies, and 6.8 cm., which is considered conservative for reflected assemblies. The experimental values of the cylinder and slab were extended to the corresponding infinite variables by conservative empirical and theoretic methods.

1. **Minimum Critical Masses**

TABLE VII
ESTIMATED MINIMUM CRITICAL MASSES

Enrichment (wt. % U-235)	Approximate Moderation (H/U-235)	Reflector	U-235 Mass (kg.)	U-235 Mass (lb.)	Ref.
~ 90	440	Water	0.79	1.74	26
~ 90	500	Air	1.4+	3.09	27
~ 90	None	Water	100++	221	3
~ 90	None	Air	130++	289	3
44.6	493	Water	0.95	2.09	27
37.5	None	Water	152	335	27
37.5	None	Air	414	913	27
29.8	220ξ	Water	1.0*	2.21	28
18.8	None	Water	373	822	27
14.7	650ξ	Water	1.2**	2.64	28
12.5	3.4	Water	248δ	547	27
4.9	450	Water	1.8	3.97	29
4.9	530	Air	2.9+	6.39	27
2.0	600*	Water	4.9	10.8	28
1.02	~ 500	Air	∞	∞	13

+ The container used to obtain the datum was of stainless steel which acts as a slight reflector for otherwise unreflected systems.
++ Conservative estimates from extrapolation of multiplication data. Cubical geometry has not been corrected to spherical geometry.
* The value given is predicted from datum which has been corrected for inhomogeneities as well as being corrected to spherical geometry.
** Extrapolation from multiplication data.
ξ The true moderation for the minimum U-235 mass may be an H/U-235 ratio of about 400. Other moderations, except those marked "None", are approximately optimum.
δ Obtained from experimental subcritical mass; multiplication of approximately 100 observed.

Generalizations

The following observations can be made from table VII and data given in the foregoing sections:

(1) The predicted minimum critical U-235 mass of a reflected system is less than 0.84 kg. and may be about 0.79 kg.
(2) For a homogeneous system, the minimum critical mass as a function of U-235 enrichment remains nearly constant for enrichments down to 15%, increases slowly for enrichments down to 5%, then increases more rapidly with further decrease in enrichment and appears to be infinite at an enrichment not less than 0.90%.

2. Minimum Critical Geometries

TABLE VIII

ESTIMATED MINIMUM CRITICAL CYLINDER DIAMETERS

Enrichment (wt. % U-235)	Container	Approximate Moderation (H/U-235)	Reflector	Diameter (cm.)	Diameter (in.)	Ref.
~ 90	Aluminum	50	Water	13.7	5.4	27
~ 90	S. Steel	55	Water	14.1	5.5	30
29.8	Aluminum	70	Water	16.8	6.6*	31
14.7	Aluminum	100	Water	19.8	7.8*	31
4.9	Aluminum	345**	Water	28.7	11.3	31
4.9	S. Steel	345**	Air	35.8	14.1*	27
2.0	Aluminum	450	Water	46.2	18.2	27

* These values have less direct experimental justification, but extrapolations used are considered to be conservative.

** Estimated from experiments with low density material.[29]

TABLE IX

ESTIMATED MINIMUM CRITICAL VOLUMES

Enrichment (wt. % U-235)	Container	Approximate Moderation (H/U-235)	Reflector	Sphere Diam. (cm.)	Sphere Diam. (in.)	Volume (liters)	Volume (in.^{3})	Ref.
~ 90	Aluminum	50	Water	21.5	8.5	5.2	317	32
~ 90	S. Steel	50	Water	21.9	8.6	5.4	330	32
~ 90	S. Steel[α]	50	Water	26.2	10.3	9.3	568	32
~ 90	S. Steel	50	Air	29.7	11.7	13.7	836	32
29.8	Aluminum	70	Water	26.2	10.3	9.2*	561	31
14.7	Aluminum	100	Water	29.2	11.5	13.2*	806	31
4.9	Aluminum	345**	Water	41.4	16.3	37.0	2260	31
4.9	S. Steel	345**	Air	48.3	19.0	58.8*	3590	27
2.0	Aluminum	450	Water	63.5	25.0	134	8180	27

* These values have less direct experimental justification, but extrapolations used are considered to be conservative.

** Estimated from experiments with low density material.[29]

α 0.02 in. cadmium shield (~ 0.44 g./cm.^{2}).

TABLE X

ESTIMATED MINIMUM CRITICAL SLAB THICKNESSES

Enrichment (wt. % U-235)	Container	Approximate Moderation (H/U-235)	Reflector	Thickness (cm.)	Thickness (in.)	Ref.
~ 90	Aluminum	50	Water	4.3	1.69	17
~ 90	S. Steel	55	Water	5.8	2.3	30
~ 90	Aluminum	44	Air	12.3	4.8	27
~ 90	S. Steel	50	Air	9.9	3.9*	2
4.9	Aluminum	345**	Water	15.2	6.0*	10
2.0	Aluminum	450	Water	25.4	10.0	27

* These values have less direct experimental justification, but extrapolations used are considered to be conservative.

** Estimated from experiments with low density material.[29]

3. Interaction Values

The interaction values listed in table XI are slightly conservative estimates of the critical solid angles for non-reflected systems which have been estimated from experimental data using an interaction theory[19] for ~ 90% U-235 enrichment material.[2,18]

TABLE XI

ESTIMATED CRITICAL SOLID ANGLE FOR UNREFLECTED INFINITE CYLINDERS AND SLABS

Cyl. Diameter (in.)	Cyl. Diameter (cm.)	Steradians (~ 90% U-235 Enrichment)	Slab Thickness (in.)	Slab Thickness (cm.)	Steradians (~ 90% U-235 Enrichment)	Ref.
5	12.7	5.0	1.25	3.18	> 12.6	27
6	15.2	3.4	1.34	3.40	6.0	27
7	17.8	2.4	2.0	5.08	4.6	27
8	20.3	0.5	3.0	7.62	2.6	27
8.1*	20.6	0	4.6*	11.7	0	27

* Individually critical.

4. Other Interaction Conclusions Implied from Experiments and Theory

a. One foot of water produces a calculated neutron attenuation of greater than 99%.[33]
b. The homogeneous system is more reactive than its heterogeneous counterpart.[21,34]
c. Due to the ORGDP method of determining equipment separation, which is based on additive solid angles, a "larger" solid angle of interaction is apparently necessary for a multi-body system to attain criticality than for a 2-body system; thus, a separation for multi-body systems based on the additive solid angle value considered safe for a 2-body system is highly conservative.
d. Interaction is more effective for the high U-235 enrichment, well-moderated system than any other system. Similarly, interaction is also more effective for a system composed of like reactors than for a system of unlike reactors with the exception of a system composed of a well-moderated unit and a dry unit at separations of the order of a few inches.
e. The effect of interaction in a system of unreflected reactors is essentially independent of the hydrogen moderation of the individual units.

2.3 THEORETICAL MINIMUM CRITICAL VARIABLES

1. Mass

A theory involving the age of the neutron indicates that for an unreflected, unmoderated UF_6C system at ~ 90% U-235 enrichment, the minimum critical mass of U-235 is 191 kg.[35]

2. Concentrations

Theoretical predictions[31] based on the Water Boiler Theory[36] indicate that ~ 90% and 4.9% U-235 enrichment uranium will not become critical where the H/U-235 ratios are greater than 2300 and 2040, respectively.

CHAPTER 3

DESIGN CRITERIA

3.1 BASIC ASSUMPTIONS

1. A thermal system requires less U-235 mass to become critical than any other system.
2. A reflected system requires no more mass of U-235 for criticality than an unreflected system.
3. Hydrogen, as found in ordinary water, is considered the most significant of the moderators and reflectors available.
4. No fissionable material having a uranium density greater than 3.2 grams of uranium/ml. (198 lb./ft.^{3}) and average uranium densities in water mixtures greater than that of UO_2F_2-water solutions at equivalent moderations will be normally encountered. (See Appendix 1, Figure 1) (Note: As a guide to acceptable values of nuclear variables for uranium materials of intermediate average densities, i.e., densities above 3.2 g. uranium/ml., see Appendix 2.)
5. Where air is the medium of separation between subcrits, interaction is considered to be a function of solid angle only and the effect of interaction is considered to be independent of the U-235 enrichment.
6. UF_6 in the gaseous phase in the quantities and configuration of existing cascade equipment cannot sustain a chain reaction.[37]
7. Uranium at a U-235 enrichment $\leq$ 0.90% cannot be made critical.[38] (See "Use of K-1019.")
8. No uranium is more reactive than that of ~ 90% U-235 enrichment. (U-233 is not considered.)

3.2 DESIGN FUNDAMENTALS

1. In order to anticipate the maximum hazard of equipment designed to handle uranium solids or liquid solutions, the system will be conservatively considered at optimum moderation, completely reflected with water, and at a U-235 enrichment of ~ 90%.
2. Geometry limitation is the primary nuclear safety control.
3. Where it is impractical to use systems of nuclearly safe geometry, non-geometrically safe equipment may be operated on the basis of a nuclearly safe U-235 mass or concentration.
4. Positive methods are used for the control of the values possible for any nuclear variable, or variables, used in maintaining nuclear safety. These include the following:

   a. Where nuclear safety is dependent upon U-235 enrichment control, positive separation of uranium materials of different enrichments is assured in order to prevent intermixing of uranium of higher enrichment than that specified for the equipment.

b. Where the U-235 enrichment is unknown, the uranium will be considered to be ~ 90% enrichment.

5. In all cases, the spacing between individual subcrits of the same or different systems will meet the basic interaction criteria.
6. Normally, nuclear poisons such as cadmium or boron, when used internally, will be considered as additional safety features but will not be relied upon for the inherent safety of subcrits; however, where standard nuclear safety geometric controls are not feasible, internal nuclear poisons may be considered for inherent safety but only provided the adequacy of the poison of concern has been specifically and rigorously determined.
7. Materials which have neutron reflecting properties greater than those of water, or which are capable of producing neutrons through nuclear reactions, will not be placed near uranium-containing equipment without special consideration. Such materials include, but are not limited to, uranium at U-235 enrichments below 0.90%, beryllium, deuterium, carbon under certain conditions, etc.

3.3 DESIGN CONCEPTS

1. <u>Nuclearly Safe Variables</u>

Unless otherwise noted, all references to dimensions in this and succeeding sections refer to the maximum actual dimensions of the uranium itself; for example, all pipe diameters are internal diameters. The definition of "nuclearly safe" as applied to the variables of geometry, mass, and concentration is defined in the Glossary (Appendix 5).

a. <u>Maximum Permissible Values</u>

The limiting values of nuclearly safe variables, where concurrent controls include only those which are generally applicable to all U-235 systems, are given in table XII together with their safety factors, which are the ratios of the estimated critical values to the corresponding nuclearly safe values of the variables concerned.

TABLE XII
MAXIMUM PERMISSIBLE VALUES

Variable	Unit	Quantity	Approximate Safety Factor
Infinite Cylinder Diameter	Inches	≤ 5.0	1.05
Infinite Slab Thickness	Inches	≤ 1.5	1.05
Volume	Cubic Inches	≤ 293	1.1
Mass	Grams U-235	≤ 350	2.3
Concentration (Water Solutions)	Grams U-235/ Liter	≤ 5.0	1.9

b. Dependence on U-235 Enrichment Control

The nuclearly safe values of the infinite cylinder diameter, sphere diameter and volume, infinite slab thickness, and the U-235 mass are shown as functions of the U-235 enrichment in tables XIII and XIV, respectively.[39,40] Table XIII should not be interpreted as implying that more than one of the variables given for the U-235 enrichment concerned must be controlled.

TABLE XIII

DEPENDENCE OF NUCLEARLY SAFE GEOMETRIC VARIABLES UPON U-235 ENRICHMENT

(See also Appendix 1, Figure 2)

Enrichment	Infinite Cylinder Diameter		Sphere Diameter		Sphere Volume		Infinite Slab Thickness	
(wt. % U-235)	(cm.)	(in.)	(cm.)	(in.)	(liters)	($in.^3$)	(cm.)	(in.)
~ 90	12.7	5.0	20.9	8.24	4.8	293	3.8	1.5
75	13.2	5.2	21.1	8.3	5.0	305	4.1	1.6
50	14.5	5.7	22.6	8.9	6.0	366	4.8	1.9
40	15.2	6.0	23.4	9.2	6.7	409	5.1	2.0
30	16.0	6.3	24.4	9.6	7.7	470	5.6	2.2
20	17.5	6.9	26.2	10.3	9.5	580	6.9	2.7
15	18.8	7.4	27.7	10.9	11.0	671	7.9	3.1
12	19.8	7.8	28.7	11.3	12.5	756	8.6	3.4
10	20.8	8.2	30.0	11.8	14.0	854	9.1	3.6
8.0	22.1	8.7	31.2	12.3	16.0	976	9.9	3.9
6.0	24.4	9.6	34.0	13.4	20.5	1260	11.4	4.5
5.0	26.0	10.25	37.1	14.6	27.0	1650	12.7	5.0
4.0	28.4	11.2	40.1	15.8	33.8	2060	14.0	5.5
3.5	30.5	12.0	42.4	16.7	40.0	2440	15.2	6.0
3.0	32.5	12.8	45.5	17.9	49.2	3000	16.5	6.5
2.5	35.6	14.0	49.8	19.6	64.6	3940	18.0	7.1
2.0	40.6	16.0	56.6	22.3	95.1	5800	22.1	8.7
1.75	44.7	17.6	62.2	24.5	126	7700	24.4	9.6
1.5	50.8	20.0	70.9	27.9	186	11,300	27.9	11.0
1.25	61.0	24.0	83.8	33.0	308	18,800	34.3	13.5
1.1	73.6	29.0	100	39.4	524	32,000	43.4	17.1
1.0	100.6	39.6	135	53.4	1300	79,600	61.0	24.0
0.90	Infinite		Infinite		Infinite		Infinite	

TABLE XIV

DEPENDENCE OF NUCLEARLY SAFE U-235 MASSES UPON U-235 ENRICHMENT

(See also Appendix 1, Figure 3)

Enrichment (wt. % U-235)	Mass U-235 (kg.)	Mass U-235 (lb.)	Mass Uranium (kg.)	Mass Uranium (lb.)	Enrichment (wt. % U-235)	Mass U-235 (kg.)	Mass U-235 (lb.)	Mass Uranium (kg.)	Mass Uranium (lb.)
~ 90	0.350	0.772	-	-	4.0	0.940	2.07	23.5	51.8
75.0	0.360	0.794	0.480	1.06	3.5	1.05	2.31	30.0	66.3
50.0	0.390	0.860	0.780	1.72	3.0	1.20	2.65	40.0	88.2
40.0	0.410	0.904	1.03	2.27	2.5	1.50	3.31	60.0	132
30.0	0.440	0.970	1.47	3.24	2.0	2.00	4.41	100	220
20.0	0.480	1.06	2.40	5.29	1.75	2.75	6.06	157	346
15.0	0.520	1.15	3.47	7.65	1.5	3.60	7.94	240	529
12.0	0.560	1.23	4.67	10.3	1.25	6.40	14.1	512	1130
10.0	0.600	1.32	6.00	13.2	1.1	12.0	26.5	1090	2400
8.0	0.650	1.43	8.13	17.9	1.0	22.7	50.0	2270	5000
6.0	0.740	1.63	12.3	27.1	0.90	Infinite		Infinite	
5.0	0.800	1.76	16.0	35.3					

c. Dependence on Controls Other Than U-235 Enrichment

(1) Mass-Volume

The amount of uranium material in any container which is not geometrically safe will normally not exceed 43.5% of the minimum critical mass of this material for the specific U-235 enrichment concerned. However, when the total capacity of the container or the volume available to this uranium material is such that no more than 80% of this minimum mass may be placed therein, the container may be completely filled.[41]

(2) Cylinder Heights and Diameters

(a) Thin-walled cylinders of aluminum or stainless steel whose dimensions do not exceed the values given in table XV are considered safe for uranium of any U-235 enrichment or moderation.[27]

(b) A right prism is safe for uranium of any moderation if its smallest cross sectional area does not exceed that of a cylinder which is safe under the same conditions as given in either table XIII or XV.

TABLE XV

NUCLEARLY SAFE CYLINDER HEIGHTS AND DIAMETERS* - ANY U-235 ENRICHMENT

(See also Appendix 1, Figure 4)

Cylinder Diameter		Height		Cylinder Diameter		Height	
(cm.)	(in.)	(cm.)	(in.)	(cm.)	(in.)	(cm.)	(in.)
12.7	5.0	∞	∞	25.4	10	10.7	4.2
14.0	5.5	85.6	33.7	27.9	11	9.4	3.7
15.2	6	44.7	17.6	30.5	12	8.4	3.3
17.8	7	21.6	8.5	38.1	15	6.6	2.6
20.3	8	15.7	6.2	91.4	36	4.3	1.7
22.9	9	12.7	5.0	∞	∞	3.8	1.5

* Based on thin wall aluminum containers.

(3) U-235 Mass and Concentration

(a) A maximum of 5000 lb. of UF_6 at 2% U-235 enrichment may be placed in a 30 in. diameter and 6 ft. long cylinder provided the amount of intermixed hydrogen is maintained below the H/U-235 moderating ratio of 3.7. Four of these chlorine-type cylinders may be stored safely in any configuration, while any number of such cylinders may be stored in a single row side-by-side with their axes lying in the same plane.[42]

(b) Gaseous UF_6 at 2% U-235 enrichment contained in 2000 $ft.^3$ surge tanks of 8 ft. diameter may be condensed safely provided each tank contains not more than 20,000 lb. of UF_6 and provided a H/U-235 moderating ratio of 3.7 is not exceeded.[43]

(c) A maximum of 21,500 lb. of UF_6 at 2% U-235 enrichment may be placed in a 48 in. diameter x 9 ft. long cylinder provided the H/U-235 moderating ratio does not exceed 3.7.[44]

(d) Thirty-two thousand pounds of UF_6 at 2% U-235 enrichment may be placed in a 36 in. diameter cylinder provided the intermixed hydrogen is maintained below the H/U-235 moderating ratio of 3.7.[45]

(e) UF_6 of any U-235 enrichment and in quantities in excess of the nuclearly safe amounts may be contained in equipment, which is not geometrically safe, provided the amount of intermixed hydrogen is maintained below the H/U-235 moderating ratios specified in table XVI.[46,47] Each container holding these quantities is then considered safe, and specified safe spacing must be maintained.

TABLE XVI

NUCLEARLY SAFE MASSES FOR SPECIFIED MODERATION - ANY U-235 ENRICHMENT

(See also Appendix 1, Figure 5)

Moderation (H/U-235)	Mass (kg.)	Mass (lb.)	Moderation (H/U-235)	Mass (kg.)	Mass (lb.)
0.01	43.0	94.8	15.0	3.3	7.3
0.1	39.8	87.7	20.0	2.5	5.5
0.5	33.6	74.1	30.0	1.70	3.75
1.0	28.5	62.8	40.0	1.34	2.95
1.5	24.2	53.4	50.0	1.10	2.43
2.0	20.0	44.1	75.0	0.80	1.76
3.0	14.8	32.6	100.0	0.65	1.43
4.0	11.5	25.4	200.0	0.41	0.90
5.0	9.5	20.9	No Limit	0.35	0.77
8.0	6.3	13.9	$\geq$ 4350	No Limit	
10.0	5.0	11.0			

(f) Under conditions where the total amount of water or other material available to moderate possible accumulations of uranium can be or is strictly limited by technical aspects of the operation itself, and evaluations show that criticality is impossible for the available uranium mixed with this limited amount of moderating material, the operation may be considered nuclearly safe.

(4) Poisons

The variables of tables XIII - XVI may be safely increased by the use of poisons, either internal or external, provided:

(a) The effect of the poison has been established experimentally.
(b) Positive measures are taken to maintain the poison in appropriate quantity (or concentration) and geometry.

2. Safe Interaction

The following criteria are used in the spacing of subcrits:

a. Interaction is considered between all equipment items which contain uranium at a U-235 enrichment above 0.90% in the solid or liquid phase except:

(1) Those where the subcrits are shielded by other subcrits whose interaction has been previously calculated.
(2) Those where the subcrits are separated by 1 ft. of material with hydrogen density as great as that of water.
(3) Among components of a system which contains a safe quantity of uranium.
(4) Those which contain homogeneous solutions with a U-235 concentration no greater than 5 grams per liter.
(5) Those where the interaction solid angle from any component is less than 0.04% of 4π (0.005 steradian).
(6) From slabs of 1/2" height or less, such as drip pans, which are perpendicular to the longitudinal center line of the cylinder or slab under consideration, or from single lines of 1/2" diameter or less, such as sight gauges.

b. Two subcrits which are dissimilar or which contain dissimilar quantities of fissionable materials will be safe if they are separated by a distance which is not less than the average of the corresponding distances by which each would be safe if separated from a subcrit which is identical to itself. This principle is also applicable to truck shipments of uranium and to other fissionable materials not normally handled at ORGDP.[34]

c. Two or more subcrits may subtend a maximum solid angle, at the most central or reactive unit, based on the calculated multiplication factor, k, for an unreflected system by the following relations:[48]

(1) For $k < 0.30$, $\Omega = 48\%$ of 4π (6.0 steradians).
(2) For $0.30 < k < 0.80$, Ω will be a straight line interpolation between 48% of 4π (6.0 steradians) and 8% of 4π (1.0 steradian). (See Appendix, Figure 6.)
(3) For cases where $k > 0.80$, direct experimental data or values reduced directly from such data will be used.

d. Interaction calculations of solid angles are computed using a distance from the center of one unit to the edge of another with the cross-sectional area of the second container assumed to be at its boundary. (For methods of computing a solid angle, see Appendix 3.)
e. In all cases, subcrits must be maintained at least 1 ft. apart, side-to-side.
f. Where interaction consideration involves more than 2 subcrits, the interaction solid angle subtended at one component due to the other units is conservatively considered to be the simple sum of the contributory solid angles from these other components.
g. The maximum solid angle for 2 interacting subcrits may be increased to values greater than the allowable values indicated in Sec. 3.3, item c, above provided the neutron shielding used is sufficient to absorb that fraction of available neutrons by which the actual solid angle exceeds the allowable solid angle.[49]
h. Where mass is the variable of nuclear safety control, the interaction effect is computed on the basis that the multiplication factor, k, is 0.65 and that the mass is contained in a spherical volume where the H/U-235 ratio is approximately 800. For the limiting value of 350 g. of U-235, this sphere is 11.4 in. in diameter.[22] The use of $k = 0.65$ for safe masses specifically includes low U-235 enrichment shipments under moderation control.
i. For systems where the multiplication factor, k, cannot readily be calculated but, from experiment, the system is known to be as safe as the subcrits meeting the criteria of table XII, a k value of 0.80 may be used. This specifically refers to safe geometries and volumes at low U-235 enrichments and to volumes containing no more than 80% of the minimum critical mass.

j. The concrete and other structural materials used in ORGDP buildings are not normally considered as neutron shielding media.

k. Where the safe quantity of uranium is based upon a limited H/U-235 moderation, the total quantity is usually contained only in a single vessel; however, if it is contained in several smaller vessels, they will be individually separated by at least 1 ft.

3. Safe Systems

Two or more subcrits are considered to form a nuclearly safe system provided:

a. Each subcrit meets the specified safe requirements for control of the U-235 mass, concentration, enrichment, or geometry.

b. Each subcrit is spaced to satisfy the requirements for safe interaction.

3.4 APPLIED DESIGN METHODS

1. Interaction

a. Equipment Connections and Turns

(1) A pipe of the maximum safe diameter as given in table XIII may not connect directly into a pipe of equal diameter; however, 90° equilaterial 'L', 'T', and '+' connections may be effected by reducing each pipe in the connection by a reduction ratio of 1.1, 1.2, and 1.3, respectively, for a distance of 3 times the safe diameter from the intersection of the pipe walls.[50,51] The maximum pipe diameters defined above for uranium of any U-235 enrichment are 4.6 in., 4.2 in., and 3.8 in., respectively.

(2) 'Y' connections at any angle may be effected between pipes provided the diameters of the connecting pipes are so reduced that the sum of the cross sectional areas of these reduced pipe sections does not exceed that of a single pipe for a minimum distance of 3 times the safe diameter from the intersection of the pipe walls and provided the reduction is also effected in those sections of pipe which are less than 1 ft. apart. These

criteria also apply to similar connections for pipe diameters which are nuclearly safe at lower U-235 enrichments.

(3) A 4 in. pipe may 'T' into a 1.5 in. slab.

(4) Several small pipes having a total cross sectional area less than that of a 4 in. pipe may 'T' into a 1.5 in. slab.

(5) A 5 in. pipe may not 'T' into a 1.5 in. slab; however, a 'T' connection may be effected if the slab is reduced to a 1 in. thickness for a radius of 7.5 in. from the center of the connection.

(6) Any number of 1 in. pipes may 'T' into a 5 in. pipe provided the points are 15 in. apart.

(7) A 5 in. pipe may be curved in a circle of 2 ft. radius provided neutron absorbing materials equal in efficiency to water are placed inside the curve. In a similar manner, a 4 in. pipe may be curved in a circle of 1 ft. radius.

b. Special Conditions

(1) Subcrits of nuclearly safe geometry, such as slabs of 1.5 in. depth or pipes with diameters of less than 5 in., are assumed to be infinite in extent except for the controlled dimensions; hence, interaction is not considered between subcrits or sections of subcrits which lie in the same plane and which have a safe slab height, or between pipes of safe geometry with the same longitudinal axis.

(2) If a group of adjacent parallel pipes can be contained in a 5 in. pipe, the pipe grouping is considered to be geometrically safe and is treated as a 5 in. pipe for interaction calculation.

(3) In determining the interaction effects of '+s', 'Ts', 'Ls', or curves, the solid angle is calculated from a position 15 in. from the point of intersection of the '+', 'T', or 'L' or 15 in. from the end of a curve.

(4) For 'Y' connections, the solid angle is calculated at the positions where the diameter reductions are effected.

c. Limiting Values of Nuclearly Safe Variables

The maximum multiplication factors, allowable interaction solid angles values, and minimum safe spacings for the limiting values of nuclearly safe variables are presented in tables XVII and XVIII.

TABLE XVII

ALLOWABLE INTERACTION VALUES

Nuclearly Safe Variables	Maximum Multiplication Factor, k	Solid Angle		Ref.
		Fractional	Steradians	
5 in. Cylinder	0.58	0.256	3.2	22
4.8 liter Volume (8.24 in. Sphere)	0.71	0.151	1.9	27
1.5 in. Slab	0.31	0.470	5.9	27
350 g. U-235 (11.4 in. Sphere)	0.65	0.200	2.5	22

TABLE XVIII

NUCLEARLY SAFE SPACING FOR DIMENSION-LIMITED CONTAINERS

(Edge-to-Edge Separations)

Dimensions	Two Units Spacing (ft.)	In Line Array Spacing[a] (ft.)	Infinite "Square" Array Spacing - (ft.)	Ref.
5 in. Cylinder[b]	1.0	1.0	4.5	27
4.8 liter Volume (Sphere)	1.0	2.5	1.0	27
1.5 in. Slab[b]	1.0	7.0	-	27

a These distances also meet safe spacing requirements when separated by the specified distance from a "twin" as is necessarily considered for shipments.
b Infinite dimension considered as 20 ft.

Note: Where applicable, containers either have their longitudinal axes parallel and/or their centers lie in the same plane.

d. Typical ORGDP Containers

The minimum safe spacing for typical containers for various uranium materials at ORGDP are presented in table XIX.[27]

TABLE XIX

NUCLEARLY SAFE SPACING FOR TYPICAL ORGDP CONTAINERS

(Edge-to-Edge Separations)

Container	Nuclearly Safe U-235 Enrichment (%)	Spacing In Line Array (ft.)[a]	Spacing Infinite "Square" Array - 2-Dimension (ft.)
5 in. I.D. x 2.5 ft.	~ 90	1.25	1.5
5 in. I.D. x 4 ft.	~ 90	1.5	2.0
8 in. I.D. x 48 in.	12.5	3.5	4.5
10 in. I.D. x 48 in.	5.9	4.0	5.0
12 in. I.D. x 40 in.	3.75	4.0	5.0
5 gal. bucket	6.5	2.0	3.0
(Mass only)	See Item b	1.0	1.5
30-gal. drum	See Item b	1.5	2.0
55-gal. drum	See Item b	1.5	2.0
30 in. I.D. x 81 in.	See Item c		
(Group of 4)[d]		4.5	5.0
(Rows)[e]		1.0	1.0
48 in. I.D. x 9 ft.	See Item c		
(Side-to-Side)		4.5	5.0
(End-to-End)		1.0	5.0

a These distances also meet the safe spacing requirements when separated by the specified distances from a "twin."
b See table XIV for U-235 enrichment limitations on U-235 mass.
c These containers are for U-235 enrichments $\leq$ 2.0% with moderation control; their longitudinal axes are parallel in a horizontal plane.
d These containers may be handled as groups of 4 in any configuration; spacing is based on groups with containers stacked 2 high.
e Any number may be placed in contact side-to-side in a row, with axes parallel and in a single plane; spacing refers to distance between rows.

General notes applicable to all cases:

1 Spacing is based on filled containers.
2 The longitudinal axes of the containers are parallel, and, unless specified otherwise, are vertical.
3 Container centers lie in the same plane for "square" array spacing.
4 Minimum separation is 1 ft. edge-to-edge except for the special cases of 30 in. I.D. cylinders. (See items d and e above.)
5 When only 2 identical container units are involved, they may be safely separated 1 ft. edge-to-edge.
6 Where mass is the control variable, $k = 0.65$ is applicable, and, where geometry is the control variable, $k = 0.8$ is applicable except for the 5 in. I.D. containers where $k = 0.58$. (Except as indicated, spacings are based on geometrical consideration.)

2. Maintenance of Safe Geometry

a. Liquid Level Control

Wherever items of equipment, such as spray tanks or piping enclosures, are of basically unsafe geometry and may contain more than a safe quantity of uranium, provisions are incorporated in the design to insure that a safe geometric configuration will not be exceeded.

(1) Pipes or overflow slots are provided in large tanks at a safe height to provide to the operator visible overflow indications of difficulties and to prevent safe dimensions from being exceeded.
(2) Uranium solution feed pumps are equipped with relays which automatically shut off the pumps when the safe slab height is exceeded.
(3) Steel plates are placed above drain connections to maintain a 1 in. solution depth for the specified area above the connection.

b. Piping and Equipment Enclosures

(1) Where below atmospheric pressure gaseous UF_6 is involved and steam is used for heating process piping and equipment enclosures, provisions are made to minimize the possibility of steam inleakage to the process.

(a) Steam lines are welded construction.
(b) The enclosures may be sealed and provided with dry ambient air under pressure, and routine humidity checks are made of the enclosure air.
(c) Where the enclosures are not of air-tight construction,

(1) routine humidity checks are made of the air in the enclosure,

or

(2) drain holes are provided at low points of the housing for the removal of condensate accumulation resulting from possible steam leakage.

(d) Steam traps, valves, condensate lines, and accessory equipment are placed outside of the piping and equipment enclosures.

(2) Where UF_6 is being condensed in cylinders or condensed UF_6 in cylinders is being vaporized, safe conditions are maintained in event of cylinder rupture.

(a) Where UF_6 is condensed in cylinders immersed in a liquid, the liquid used will have the properties of a 'neutron poison'. Such materials as trichloroethylene, freon, liquid nitrogen, etc., have these properties.

(b) Containers of UF_6, or other uranium materials, are heated with hot water or steam coils, electrical heaters, or, in special cases, by live steam. In all cases, the heating enclosure is equipped with adequate drain holes or is so sized that, in event of uranium leakage, the geometry of the uranium will not exceed the safe dimensions given in tables XIII or XV.

c. Piping and Equipment Insulation

Where piping or equipment must be insulated but leakage of uranium is considered possible, the effect of such leakage entering the insulation is considered in establishing safe conditions which are maintained by several methods.

(1) Insulation directly applied to the piping or equipment is considered to be a part of the overall geometry of the container; thus, where geometry is the control factor, the maximum dimensions of the container and insulation will not exceed the values given in tables XIII and XV.

(2) Where insulation is not applied directly to the piping, a safe condition is maintained by enclosing or shielding the insulation and by providing openings between the piping and the insulation shield for solution drainage in the event of leaks.

(3) Where a uranium container is concentrically placed in a second geometrically safe container, leakage of uranium solution is considered possible from the inner cylinder but highly improbable from two such containers. The shielding of insulation applied to the outer container or the installation of drains is not considered necessary for this arrangement.

CHAPTER 4

OPERATION CRITERIA

4.1 BASIC OPERATION PHILOSOPHY AT ORGDP

1. The possibility of malicious or intentional damage is not considered a factor in establishing criteria for nuclearly safe operation.
2. An operation will be considered safe if it requires that a double contingency must occur before a uranium configuration can become unsafe. Additional random factors of safety, which are known to exist, are not included as a basic nuclear safety specification.
3. If the U-235 enrichment and amount of any uranium material are unknown, the material will be considered to be ~ 90% U-235 and will be placed in geometrically safe containers until analyses are obtained to show the safe disposition of the material.
4. Only specifically designated groups are authorized to make up safe amounts of uranium and to process these safe amounts through recovery operations.
5. No uranium-containing equipment other than that specifcally approved for an operation may be brought into an operating area.
6. No more than 1 subcrit may be in motion at any one time in an operating area, and it must reach the approved destination via an approved route before another subcrit may be moved in that area.
7. Routine surveys for the detection of uranium will be made of all unsafe equipment where material accumulations are not normally expected but where they might occur as a result of equipment failure, misoperation, or other abnormal conditions. This applies particularly to cascade operations.
8. Radiation detection instruments with automatic alarms are installed at intervals throughout the process and decontamination and recovery areas for the detection of any critical mass occurrence.
9. In the absence of wet air inleakage, all cascade condensations are considered to be essentially unmoderated, a maximum hydrogen to uranium ratio of 0.1 being used in determining equipment safety.
10. The presence of enriched uranium in any location is not alone sufficient justification to prohibit the planned use of water in fire control activities, but such usage should be carefully controlled.[52]

4.2 APPLIED OPERATION TECHNIQUES

1. General

   a. Where it is impractical to obtain isotopic analyses, chemical analyses are obtained and uranium material is handled in equipment which is not geometrically safe on a total uranium mass basis of 350 grams.

b. Properly spaced safe containers are used for temporary storage and handling of reactive uranium materials.

c. Physical spacers in the form of guide rails, posts, and chains, as well as painted guide lines, are used to aid employees in storing and moving subcrits so that a safe geometry is maintained at all times. Specially built dollies and trucks are also used to maintain correct spacing of subcrits during transit.

d. Monitoring of cascade equipment with portable radiation detection instruments is done on both routine and special check bases for the detection of accumulations of uranium material which may be caused by small air leaks or other operational difficulties.

e. Where "dead-end" systems result from operational changes, they are removed from operation by cutting and blanking the lines, or are isolated by border valves.

f. When equipment is removed from the cascade, the openings are immediately covered to reduce the absorption of atmospheric moisture by any uranium compounds contained therein.

g. In addition to the coverings specified in Section 4.2, item 1.f, for cases where an accumulation of uranium is known to exist or is suspected in equipment which is removed from the cascade, a dry air or nitrogen bleed is placed on the equipment to reduce further the absorption of atmospheric moisture.

h. In liquid UF_6 withdrawal operations, a safe H/U-235 ratio based on solubility of HF in UF_6[53] is maintained by controlling condenser temperatures and pressures within specified limits.

i. Steam, which is manually controlled, is used as a means of quickly disposing of UF_6 gas from the atmosphere in event of release so that appropriate action may be initiated to correct the difficulty; however, the steam nozzles are positioned so that the steam is not sprayed directly on any system components containing moderation-limited UF_6.[54]

2. <u>Other Operations</u>

a. For decontamination purposes, the U-235 enrichment of material removed from cascade equipment is considered to be the maximum enrichment at which the equipment was operated as indicated by uranium accountability records.

b. In general, uniformity of sampling is controlled through the use of 2 separate samples taken at different times during the blending operation and individually analyzed. The results of the analyses should agree within 5%.

c. Non-geometrically safe equipment, which is decontaminated in spray booths or wash tables, is positioned so that solution is not held up in the equipment.

d. The identity of a safe amount of uranium contained in each of 2 non-geometrically safe equipment items may be maintained by:

   (1) Breaking all connections between equipment items.
   (2) Installing blank flanges in the interconnecting lines.
   (3) Opening a drain or "tattle-tale" valve between the block valves in the interconnecting lines.

e. Administrative controls used in conjunction with the items in Sec. 4.2, item 2.d include:

   (1) "Danger-Do Not Operate" tags, which are signed by supervision to indicate that the condition in effect is not to be changed without specific authorization.
   (2) Check-off sheets, which are completed and signed by operating personnel, indicating that provisions for nuclearly safe operation are in effect.

APPENDIX 1

GRAPHS

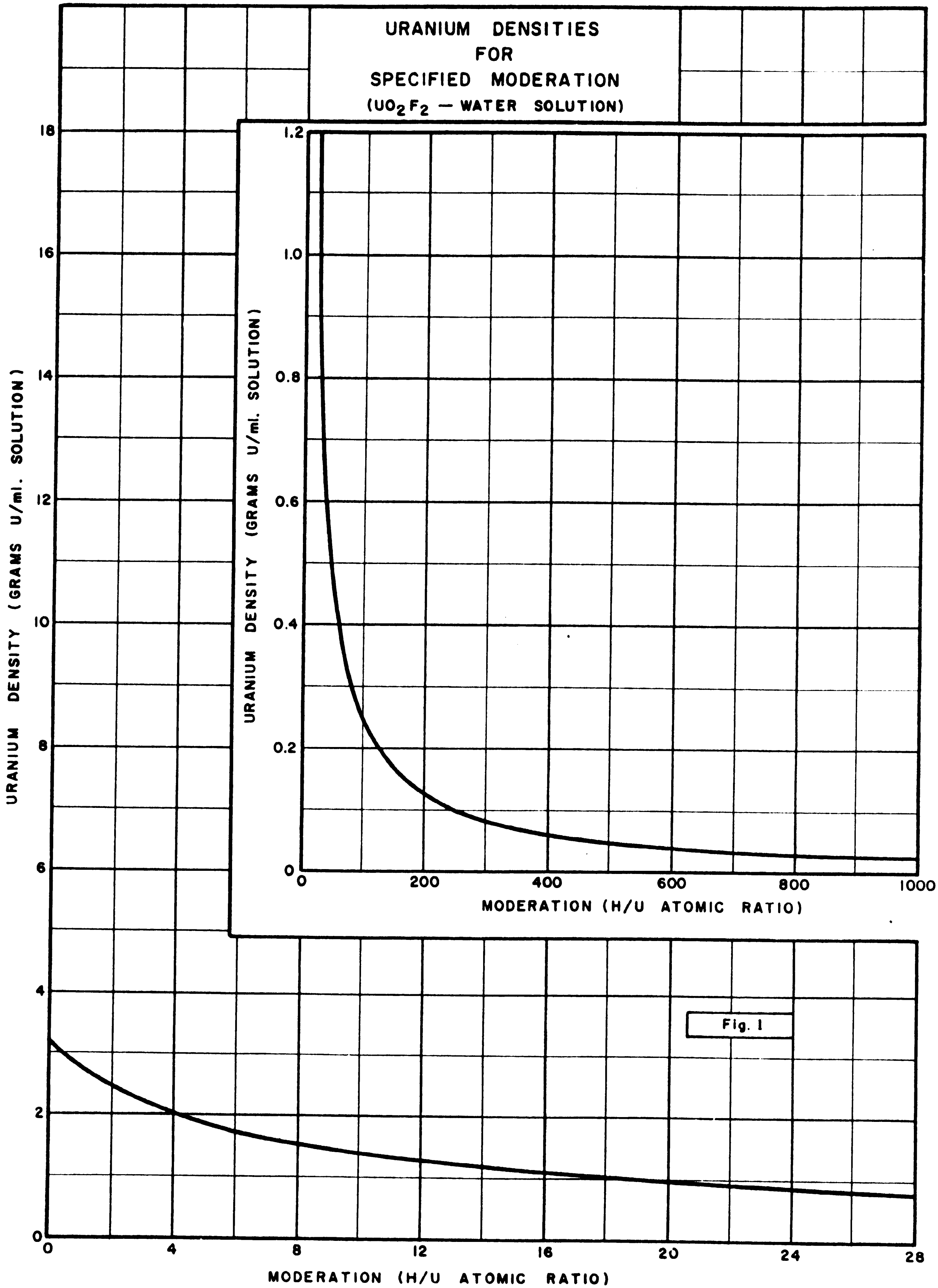

URANIUM DENSITIES
FOR
SPECIFIED MODERATION
(UO_2F_2 — WATER SOLUTION)
URANIUM DENSITY (GRAMS U/ml. SOLUTION)
0
2
4
6
8
10
12
14
16
18
0
4
8
12
16
20
24
28
MODERATION (H/U ATOMIC RATIO)
URANIUM DENSITY (GRAMS U/ml. SOLUTION)
0
0.2
0.4
0.6
0.8
1.0
1.2
0
200
400
600
800
1000
MODERATION (H/U ATOMIC RATIO)

Fig. 1

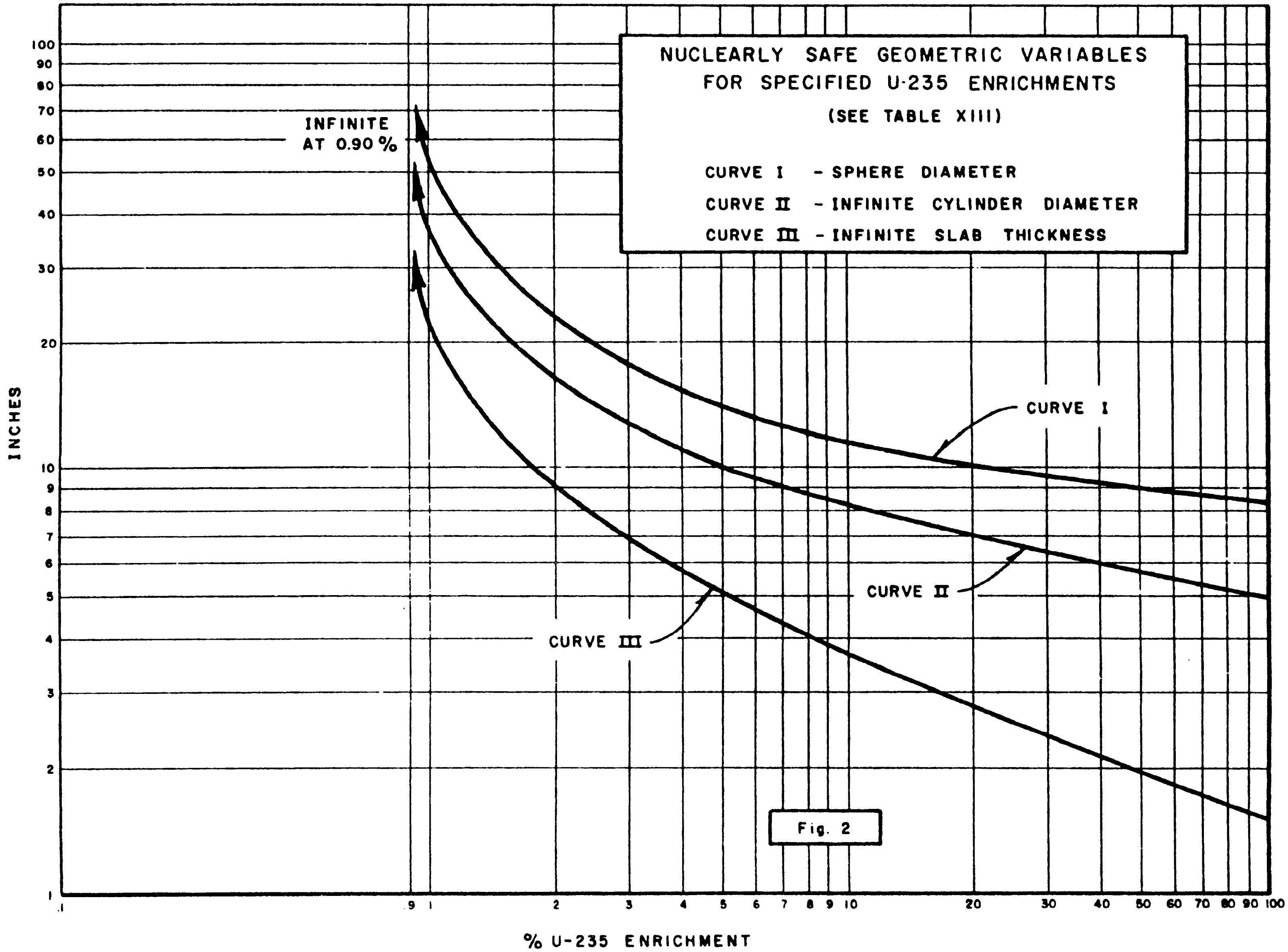
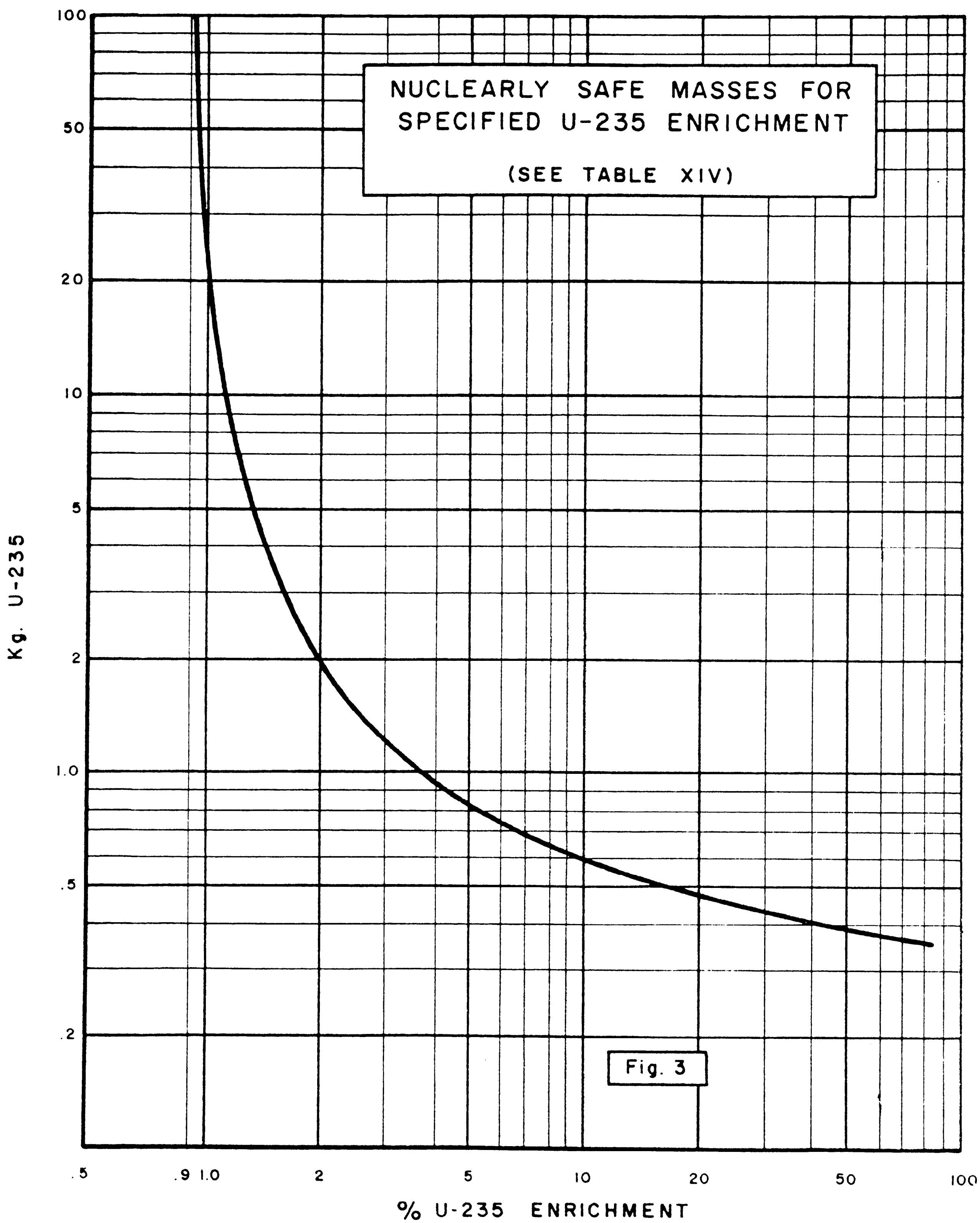
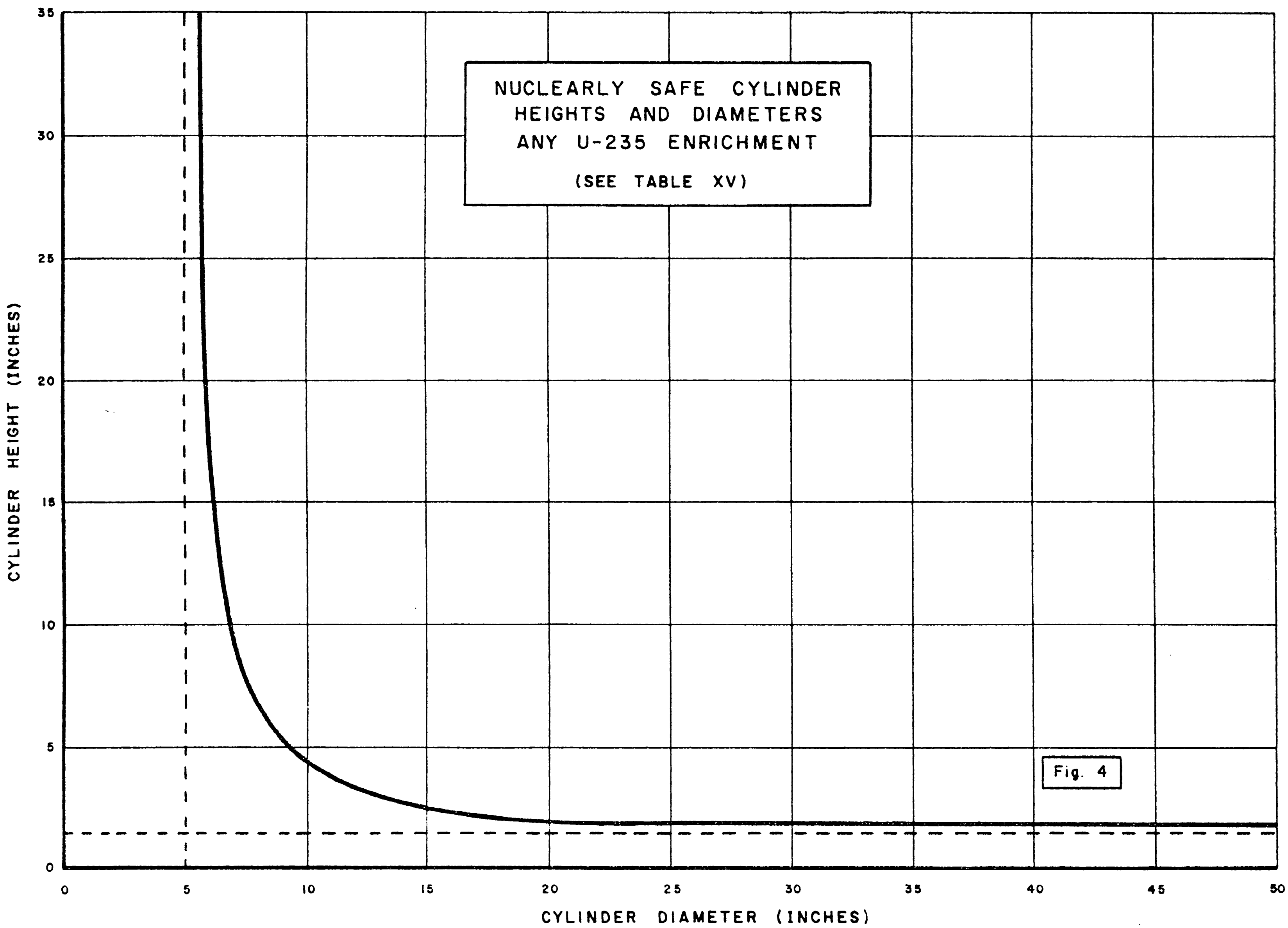

NUCLEARLY SAFE GEOMETRIC VARIABLES
FOR SPECIFIED U-235 ENRICHMENTS
(SEE TABLE XIII)
CURVE I - SPHERE DIAMETER
CURVE II - INFINITE CYLINDER DIAMETER
CURVE III - INFINITE SLAB THICKNESS
INFINITE
AT 0.90 %
CURVE I
CURVE II
CURVE III
INCHES
% U-235 ENRICHMENT
100
90
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
.1
.9
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
80
90
100

Fig. 2


NUCLEARLY SAFE MASSES FOR
SPECIFIED U-235 ENRICHMENT
(SEE TABLE XIV)
Fig. 3
Kg. U-235
100
50
20
10
5
2
1.0
.5
.2
.5
.9 1.0
2
5
10
20
50
100
% U-235 ENRICHMENT


NUCLEARLY SAFE CYLINDER
HEIGHTS AND DIAMETERS
ANY U-235 ENRICHMENT
(SEE TABLE XV)
CYLINDER HEIGHT (INCHES)
CYLINDER DIAMETER (INCHES)
0
5
10
15
20
25
30
35
40
45
50
Fig. 4

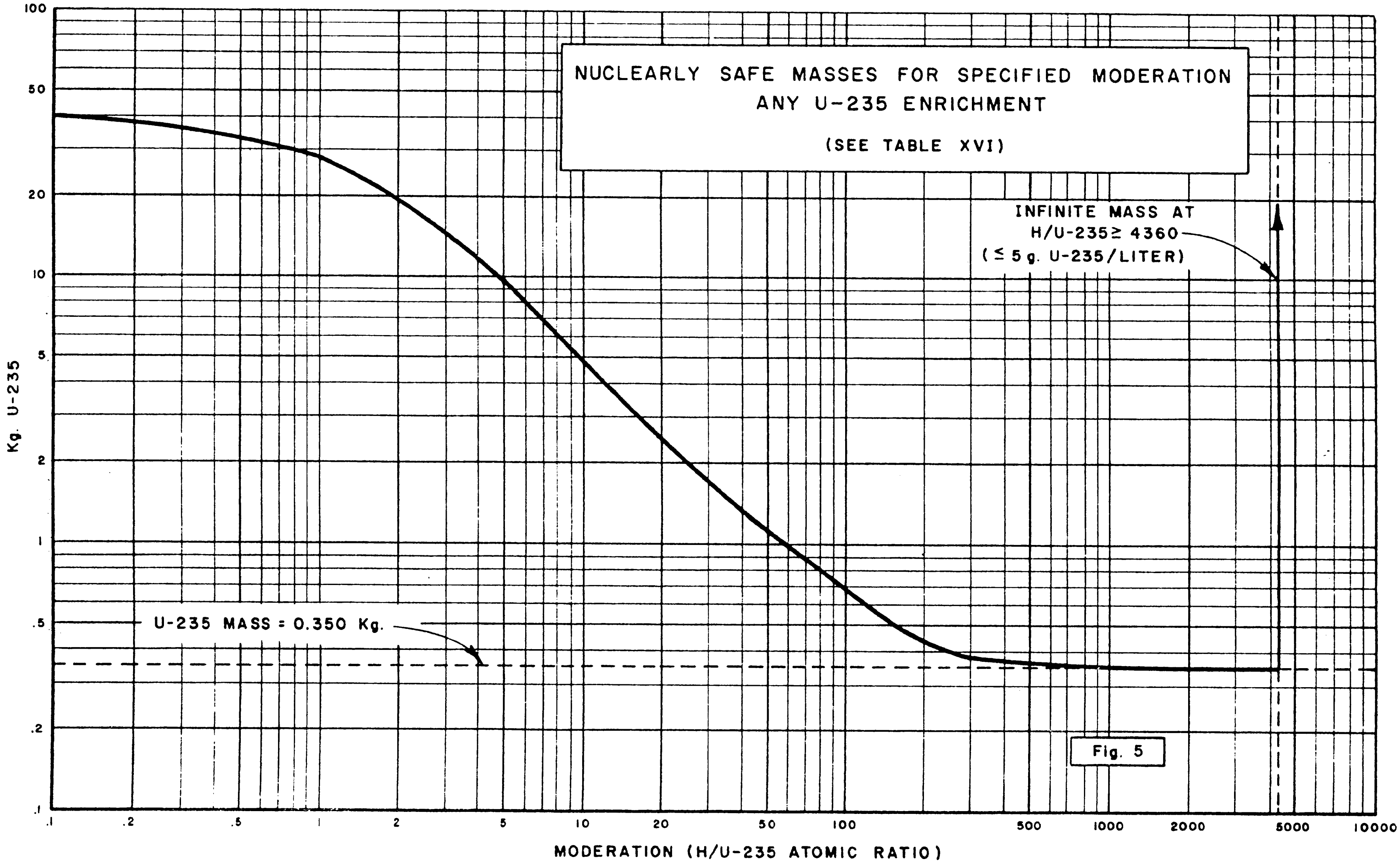

NUCLEARLY SAFE MASSES FOR SPECIFIED MODERATION
ANY U-235 ENRICHMENT
(SEE TABLE XVI)
INFINITE MASS AT
H/U-235 ≥ 4360
(≤ 5 g. U-235/LITER)
U-235 MASS = 0.350 Kg.
Kg. U-235
100
50
20
10
5
2
1
.5
.2
.1
.1
.2
.5
1
2
5
10
20
50
100
500
1000
2000
5000
10000
MODERATION (H/U-235 ATOMIC RATIO)

Fig. 5

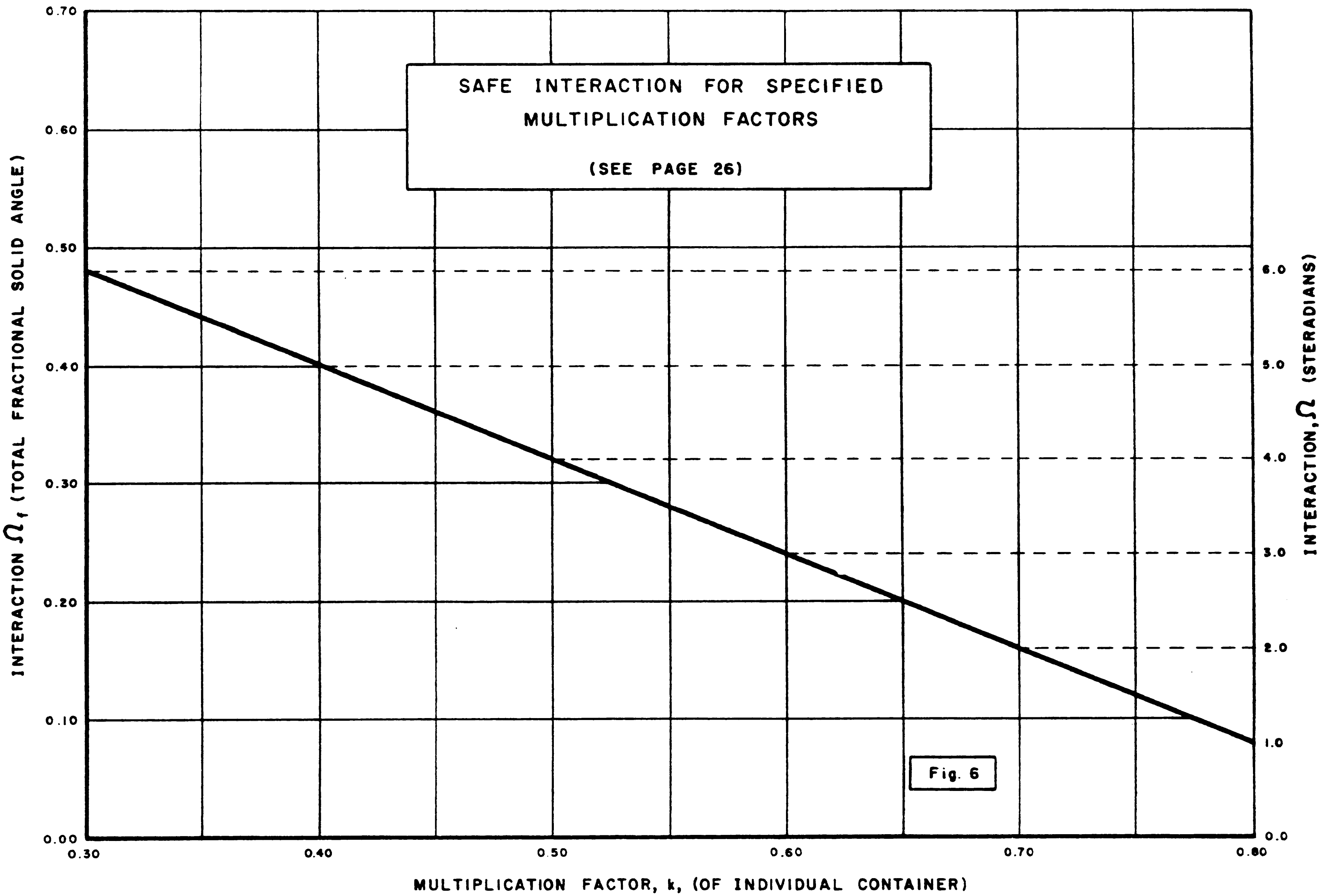

SAFE INTERACTION FOR SPECIFIED MULTIPLICATION FACTORS
(SEE PAGE 26)
INTERACTION Ω_f (TOTAL FRACTIONAL SOLID ANGLE)
INTERACTION, Ω (STERADIANS)
MULTIPLICATION FACTOR, k, (OF INDIVIDUAL CONTAINER)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.0
1.0
2.0
3.0
4.0
5.0
6.0
0.30
0.40
0.50
0.60
0.70
0.80

Fig. 6

APPENDIX 2

CRITERIA FOR HANDLING MATERIALS OF INTERMEDIATE DENSITIES

1. These criteria refer to uranium materials having intermediate average densities and specifically include dry uranium salts which have densities above 3.2 g. uranium/ml. (198 lb. uranium/ft.^{3}) and have average uranium densities in water mixtures or solutions greater than those of UO_2F_2-water solutions at equivalent moderations.

2. As guides to acceptable values of the nuclear variables for these materials, the appropriate limiting values of mass, volume, and linear dimensions may be determined for the material of higher density, ρ, by reducing the values in tables XII to XV by the following ratios where ρ_o is given by the curve of Appendix 1, Figure 1 for the moderation of concern:

   a. Linear dimension (ρ_o/ρ)

   b. Mass $(\rho_o/\rho)^2$

   c. Volume $(\rho_o/\rho)^3$

3. The uranium density of these systems is determined as follows:

   a. For water solutions, suspensions, or mixtures of a high density salt, the uranium density used is that of the material at the given moderation of concern. (Note: As a generally applicable criterion for these materials, the uranium density used, ρ, may be that of the unmoderated material, and ρ_o may be 3.2 g./ml.)

   b. For metal pellets, etc., this density is the simple ratio of the metal mass to the gross volume occupied by the material, and the moderation of concern is assumed to be obtained by filling the interstices with water.

4. The value of the variable determined from these corrections is <u>always</u> less than the tabular figure for corresponding conditions of moderation, U-235 enrichment, etc. (Note: This implies that the average uranium density of the intermediate density material is greater than 3.2 g./ml.)

APPENDIX 3

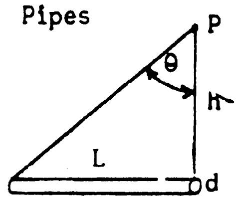
Solid Angle Calculations

A. Formulae

1. General

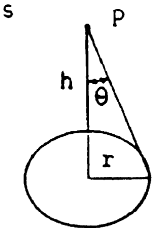
$$\Omega = \frac{\text{Cross Sectional Area}}{(\text{Separation Distance})^2}$$

2. Pipes



$$\Omega = \frac{d}{h}\, \text{Sin}\, \theta$$

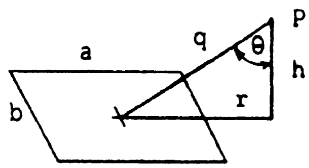
3. Discs



$$\Omega = 2\pi\,(1 - \cos\theta)$$

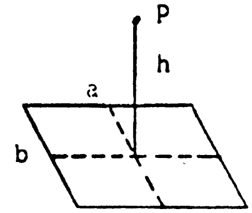
4. Planes

a.



$$\Omega = \frac{ab\cos\theta}{q^2}$$

b.

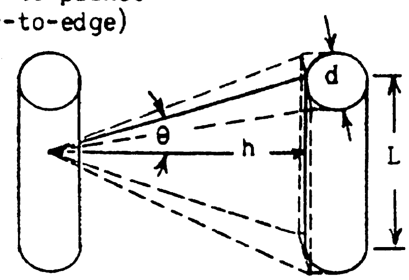


$$\Omega = 4\,\text{Sin}^{-1}\frac{(\frac{a}{2})\,(\frac{b}{2})}{\sqrt{(\frac{a}{2})^2 + h^2}\,\sqrt{(\frac{b}{2})^2 + h^2}}$$

B. Applied Methods

1. Cylinders

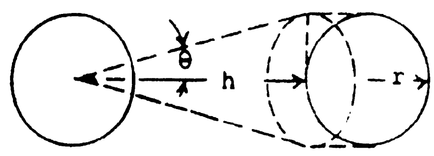
(Reduce to planes
Center-to-edge)



$$\Omega = \frac{2d}{h}\, \text{Sin}\, \theta$$

2. Spheres

(Reduce to discs
Center-to-edge)



$$\Omega = 2\pi\,(1 - \cos\theta)$$

CONVERSION OF FRACTIONAL SOLID ANGLE, Ω_f, TO STERADIANS

Ω_f	Steradians	Ω_f	Steradians	Ω_f	Steradians
1.000	12.56 (4π)	0.350	4.40	0.100	1.26
0.750	9.42 (3π)	0.250	3.14 (π)	0.050	0.63
0.500	6.28 (2π)	0.150	1.88	0.000	0.00

APPENDIX 4

OAK RIDGE GASEOUS DIFFUSION PLANT

PLANT SUPERINTENDENT

ASSISTANT PLANT SUPERINTENDENT-

Industrial Relations

ASSISTANT SUPERINTENDENT

Industrial Relations

Division

DEPARTMENT HEAD

Safety, Fire, and Radiation

Control Department

SUPERVISOR

Nuclear Safety Section

LINE SUPERVISION

ORGDP CRITICALITY HAZARDS

COMMITTEE

Manager of Production
Plant Superintendent, ORGDP
Plant Superintendent, Paducah
Asst. Plant Superintendents
Division Superintendents
Approvals Committee
Department Heads

APPROVALS COMMITTEE

Department Head - Safety, Fire, and Radiation Control - Chairman
Supt. Operations Analysis Division
Department Head - Critical Mass Research (ORNL)
Research Physicist (ORNL)

CONSULTANTS COMMITTEE

To include 3 or more scientists not associated with the ORGDP.

OAK RIDGE GASEOUS DIFFUSION PLANT

ORGANIZATION FOR NUCLEAR SAFETY

CONTROL*

* Reference 55

APPENDIX 5

GLOSSARY

Brief definitions of some of the special terms used in this report are given below. In a few cases, the terms may have rather special meanings with respect to nuclear safety as compared to other fields of nuclear technology, and one word, "subcrit," is completely original.

ATTENUATION	A reduction in the intensity of neutron flux upon passage through material.
"BIRDCAGE"	A term used to refer to an outer container or framework surrounding and rigidly centering a vessel which actually contains fissionable material; the principal function of this "birdcage" is the maintenance of designated spacing between individual vessels containing fissionable material.
BORAL	A boron carbide-aluminum complex with high neutron absorption properties.
CONSERVATIVE	A term applied to calculations or other estimates where the factors are so chosen that criticality is predicted for an experimentally subcritical assembly, and, correspondingly, a critical assembly is predicted to be supercritical.
CONTINGENCY	A possible but unlikely and uncontrollable change in one or more of the conditions originally specified as essential to the nuclear safety of a specific operation or activity such that the nuclear safety of the operation or activity is decreased. (See Double Contingency.)
CORE	The region containing the fissionable material in a reactor or a subcrit; sometimes refers to the fissionable material itself.
CRITICAL(ITY)	The state of, or attaining the status of, a self-sustaining nuclear chain reaction; maintenance of a chain reaction with a constant neutron flux in the absence of a neutron source.
CRITICALITY CONTROL	Efforts made to prevent a criticality incident; this usually requires the imposition of physical or administrative limitations, or both, to one or more of the nuclear variables of a given system such that criticality is impossible so long as these limitations are maintained.
CRITICALITY INCIDENT	The unplanned and unexpected attainment of criticality; a nuclear excursion in a system other than that of a reactor or an experimental setup.

CRITICAL MASS — The mass of fissionable material (U-235) at criticality; the minimum mass of fissionable material (U-235) which can be made critical under a specific set of conditions.

DOUBLE CONTINGENCY — Two independent contingencies which are concurrent in time.

a. Contingencies are independent if the occurrence of either one does not cause the other or affect its probability of occurrence.

b. Concurrent in time implies (1) that both contingencies can occur in a shorter interval of time than normal review for correction of any uncontrolled change in the value of a variable is scheduled, or (2) that corrective action cannot be taken to control the first event prior to the occurrence of the second one.

ENRICHMENT, U-235 — U-235 isotopic concentration, usually expressed as the weight percent of U-235 in uranium; also referred to as U-235 assay. (Example: Since 0.7115% of virgin (naturally occurring) uranium is the U-235 isotope, this uranium is said to be at a 0.7115% U-235 enrichment or at a U-235 assay of 0.7115%.)

FISSION — The division of a heavy nucleus into two approximately equal parts with an attendant release of neutrons and relatively large amounts of energy in the form of heat and radiation.

FISSIONABLE MATERIAL — Those materials in which nuclear fission can result in a chain reaction with the emission of a large amount of energy. At present, only U-235, U-233, and Pu-239 are considered significant fissionable materials, and U-235 is the only one of these occurring naturally. (Note: U-235 only is considered in this guide.)

HALF REFLECTION — Interpreted as that condition where a core is completely reflected over 50% of its surface area. (See Reflection.)

HETEROGENEOUS — Non-homogeneous; a core wherein segregated masses of moderator and fissionable material can be either randomly or regularly spaced. (See Homogeneous.)

HOMOGENEOUS — The arrangement of nuclei in a core such that the density of both fissionable and other atoms, averaged over regions small compared to the neutron mean free path, is constant. (Example: Water solutions of uranium compounds are homogeneous.) (See Heterogeneous.)

H/U-235 RATIO	The ratio of the number of hydrogen atoms to the number of U-235 atoms in a core. (See Moderation.)
INTERACTION	The mutual interchange of neutrons between the units in a system of subcrits; it is also considered as the probability that an escaping neutron will enter another subcrit.
INVENTORY	The total amount of U-235 present in a unit or vessel; usually given in terms of the total uranium and the U-235 enrichment. As applied to production equipment, this may also refer to the total quantity of uranium or UF_6 in the unit.
MODERATION	A slowing down of neutrons from the high velocities (and correspondingly high energies) at which they are produced to velocities (and corresponding energies) at which the probability of fission capture in U-235 nuclei is relatively large; usually expressed as a ratio of the number of moderator atoms and fissionable atoms. (See H/U-235 Ratio; Moderator.)
MODERATOR	A material having nuclear properties producing moderation. As a general premise, materials whose atomic weights are not significantly different from that of a neutron are good moderators; of these, hydrogen is usually the moderator of greatest concern.
MULTIPLICATION FACTOR, k	The ratio of the number of neutrons present at a given time to the number present one neutron generation earlier in the absence of a neutron source. For criticality, k = 1. (Note: As used in this guide, k refers to the factor identified in reactor technology as $k_{effective}$, the effective multiplication factor for the container considered.)
NEUTRON	An elementary particle of mass number 1 and no electrical charge; in nuclear reactions, it is important as the fundamental particle that initiates fission in U-235.
NEUTRON MULTIPLICATION, M	The ratio of the total number of neutrons in a subcrit or subcritical reactor containing a neutron source to the smaller number of primary source neutrons. Given by the relation: $M = 1/(1-k)$. As k, the multiplication factor, approaches 1, M approaches infinity.

NUCLEAR HAZARDS	Those sources of risks to nuclear radiation or physical damage, which may arise from accidental or inadvertent establishment of criticality.
NUCLEAR PARAMETERS	Those generalized factors which are inherent in the description of the nuclear safety of a subcrit and which are expressed practically as nuclear variables. (See Nuclear Variables.)
NUCLEAR VARIABLES	Those factors by which the various nuclear parameters are expressed in specific situations and to which predetermined limiting values can be assigned in defining the nuclear safety of a specific subcrit or system of subcrits. (See Nuclear Parameters; Subcrit.)
NUCLEARLY SAFE	Refers to subcrits or systems of subcrits where the permissible values of one or more nuclear variables are so limited by equipment dimensions or other physical factors that criticality cannot occur even though no limitation is placed upon possible values of other variables; this may also refer to the limit values of these variables. (Note: The limit value for any one variable may require or imply concurrent limitations on the permissible values of other variables and such concurrent limitation is inherent in this definition.)
POISON, NEUTRON	A non-fissioning material with neutron absorption cross sections which are comparatively high with respect to other nuclear properties of the same material or those of other materials in the same system.
REACTOR	A container or assembly of fissionable materials designed to permit a controlled nuclear chain reaction; a planned critical system. The term "reactor" may be modified by the words thermal or fast to indicate the energy of the neutrons which predominate in maintaining the reaction.
REFLECTION	The return of neutrons escaping from a core. (See Reflector.)
REFLECTOR	Materials having, in various degrees, the property of reflection; a configuration wherein material having the nuclear properties of reflection surrounds a core. (Note: Since all materials reflect neutrons to some extent, this becomes an important factor in determining nuclear safety. For maximum safety considerations in transportation, a subcrit is designed to be safe when completely surrounded by a water reflector.)

SHIELD, NEUTRON	A layer of material around a core with the primary function of preventing the escape of neutrons into the space surrounding the core; also, material reducing or eliminating interaction between cores. Since 1 foot of water has over 99% attenuation of fission neutrons, it is considered to be a good neutron shield.
SLAB	A container having 2 parallel plane surfaces whose combined area is greater than 50% of the total surface area.
SOLID ANGLE	The ratio of that portion of the area of a sphere which is enclosed by the conical surface forming the solid angle, to the square of the radius of the sphere; denoted by the Greek letter, Ω. (See Steradian.)
SPACER	Individual unit or system designed to maintain a given minimum separation between any container and a vessel or vessels containing uranium. A "birdcage" is a specific type of spacer.
STERADIAN	A unit of solid angle defined as that angle which is subtended by a surface area on the sphere numerically equivalent to the square of the radius. The total solid angle in space is thus 4π steradians. (See Solid Angle.)
SUBCRIT	A quantity of fissionable materials contained under such conditions that a self-sustaining chain reaction is impossible under the specified limitations; a subcritical core or system; the vessel and its contents of fissionable material meeting these specifications.
SUBCRITICAL	Refers to an accumulation of fissionable material under such conditions that a nuclear chain reaction will not occur; a system with a multiplication factor, k, of less than 1.
SUPERCRITICAL	Refers to a critical accumulation of fissionable material with an increasing neutron population and a correspondingly rising rate of neutron fission; a system with a multiplication factor, k, larger than 1.
"TWIN"	A reactor or subcrit having nuclear properties identical to those of another reactor or subcrit.
U-235	Uranium with an atomic weight of 235; this comprises about 0.7115% of virgin (naturally occurring) uranium.

APPENDIX 6

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